

Air-Water Gas Transfer in Coastal Waters

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LONG-TERM GOAL

The long-range objective of this project is the physical parameterization of the air-sea gas transfer rate. In order to accomplish this goal, novel experimental techniques and instrumentation have been developed for in situ measurements of the gas transfer rate and the processes and parameters controlling it. These instruments were deployed during field experiments to investigate the mechanisms of air-water gas transfer.

OBJECTIVES

In interdisciplinary field experiments the influence of wind forcing, short wind waves, and surfactants on the air-sea gas transfer in coastal waters is studied. The measurements include the air-sea gas transfer rates with a temporal resolution in order of minutes, the air friction velocity, water currents and turbulence, air and water temperatures, visible and infrared (IR) radiative fluxes, the visco-elastic properties of surface films, and wave number-frequency spectra of short wind waves. The measurements of the air-sea gas exchange rates with our instruments were combined with concentration measurements of carbon dioxide and dimethyl sulfide in the sea and the atmosphere, and direct flux measurements of carbon dioxide using the eddy correlation technique.

APPROACH

Using heat as a proxy tracer, the transfer rate is measured locally and with a temporal resolution of less than a minute. This technique offers an entirely new approach to measure air-sea gas fluxes of arbitrary gases and to simultaneously observe the micro turbulence at the ocean interface. Measuring the spatiotemporal temperature distribution on top of the aqueous mass boundary layer, heat patterns can be observed that directly reveal the horizontal structure of surface-near turbulence. Hence, direct insight into the transport processes right at the air-water interface is obtained through quantitative analysis of infrared image sequences of the water surface temperature. Our main focus during the last year was on the development of data analysis techniques that allow the extraction of the relevant features from the spatiotemporal image data. Together with physical modeling of the underlying transfer processes, the passive infrared radiometry technique allowed the computation of the transfer

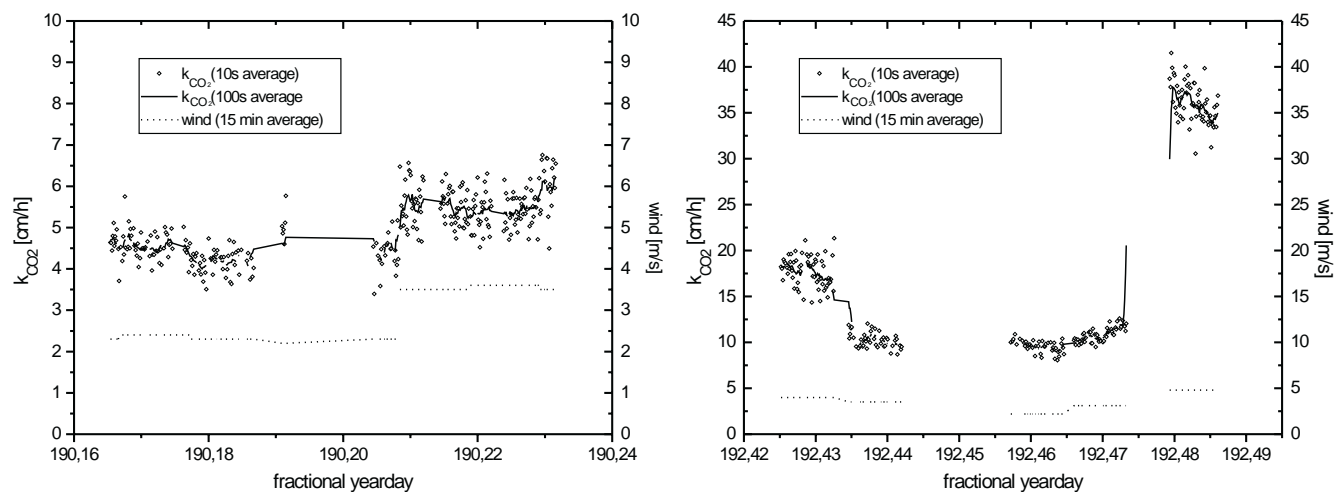
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rates directly from the statistical surface temperature distributions without artificial heating of the water surface.

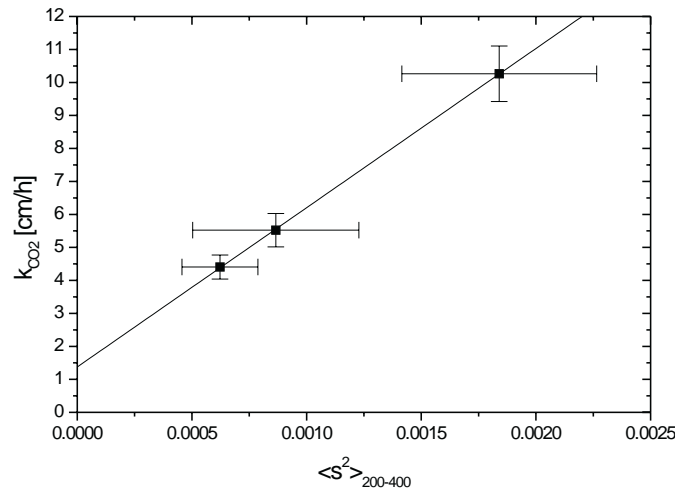
The passive infrared technique has been used successfully to evaluate extended data sets acquired during the 1997 field experiment in the North Atlantic between the coastal waters of Martha's Vineyard sound south of Cape Cod, MA, and the Bermuda islands. This project was conducted in cooperation with Dr. Erik Bock, Dr. Nelson Frew, Dr. James Edson from WHOI, and Dr. Tetsu Hara from the University of Rhode Island. Further field experiments were conducted from Scripps Pier, SIO.

WORK COMPLETED

The last year was devoted to the development and improvement of multidimensional data analysis techniques, and to the evaluation of data from both field experiments as well as the laboratory measurements. In order to capture the dynamics of the heat patterns on the ocean surface, it is necessary to reliably track the structures in the infrared images without bias from the dominant system noise of the infrared imager. This task is further burdened by the fact that the structures of interest change their shape and brightness along their trajectory. This could not be handled by state-of-the art image processing techniques and new algorithms had to be developed. A major breakthrough was achieved a novel motion estimation technique that incorporates the physical transport processes into the motion analysis and tracking of the heat patterns (Haussecker et al., 1999). This resulted in increased accuracy of the motion estimation, and allowed the direct computation of the physical parameters of the underlying transport processes. Preliminary experiments verified that it is also possible with this technique to estimate the net heat flux across the air-water interface from infrared image sequences. A systematic study of both field and lab data allowed us to further refine and verify the model assumptions for the statistical surface renewal model used to compute gas exchange rates from the passive infrared technique. We could prove that the technique gives reliable estimates of the bulk temperature, and hence the bulk-skin temperature difference across the ocean surface.



1. Transfer velocity and wind speed (at 18m above the water surface) vs. time (fractional yearday). The left plot shows a low wind speed case without rain. The right plot shows a rain sequence with moderate rain around YD192.43, no rain between YD192.35 and 192.47 and heavy rainfall between YD192.475 and YD192.485.



2. Results of the parameterization of gas exchange rate, k_{CO_2} , by the wave-number-binned mean square slope, $\langle S^2 \rangle_{200-400}$, obtained from the second CoOP field experiment. Each point represents a 15 minute average (variance denoted by error bars) obtained under homogeneous conditions of meteorological forcing and surface characteristics.

During the 1997 field experiment, the gas exchange rates estimated by the passive infrared technique were compared with measurements of directional ocean surface wave spectra with wavelengths between .004 and 10.0 meters from the LADAS research catamaran. Both laboratory studies and field experiments suggest that slope statistics of short waves are related to the rate of gas exchange across the air-sea interface. Concurrent measurements of the gas transfer rates and mean square wave slope within the same footprint were used to further refine this relation.

RESULTS

During the CoOP East Coast experiment from July 1 to July 18, 1997, the CFT instrument was used for the second time in the field. Although no high wind speeds were encountered (maximum 8.4 m/s), the experimental conditions include a large variability. Physicochemical surface conditions ranged from coastal waters with high surfactant concentrations to very clean, deep blue waters close to the Bermuda islands.

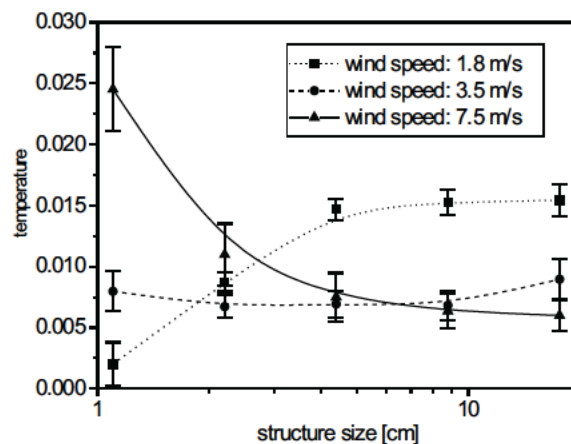
The research cruise produced data which show that the CFT is capable of making fast measurements of gas transfer rates that follow the course of wind speed. Two time series of CO_2 transfer velocities measured during the cruise are shown in Fig. 1, together with 15min averages of the measured wind speed. The left side of Fig. 1 shows that the gas transfer rates follow the course of the wind speed with a sudden increase of both wind speed and gas transfer around Year Day (YD) 190.21. Although the transfer rates match field measurements of other techniques in the statistical average—such as the differential tracer and the radon deficiency method—, some features of these time series are not explained using solely wind stress. Intermittent fluctuations on short time scales seem to be related to other modulating mechanisms, like the occurrence of rain and the presence of surface films. An example of the strong influence of rain on modulating gas exchange is demonstrated on the right side

of Fig. 1. During the times reported for YD192 the weather changed from moderate rain to heavy rain with a period of no rain in between. While the wind speed remained low, between 3 and 5 m/s, the gas transfer rates show an increase of almost a factor of four with the onset of heavy rain. From this example two important conclusions can be drawn:

- 1 The CFT technique is capable of measuring gas transfer rates even during heavy rain.
- 2 Gas transfer rates are subject to strong variations during intermittent meteorological conditions.

To date, all field data of gas transfer rates show that wind speed alone is not sufficient to parameterize air-sea gas transfer. Residual intermittence in the high-resolution CFT data is likely to be caused by surfactants and other surface-related properties that exhibit regional and temporal variations. Recent measurements show that mean square wave slope is more adequate to parameterize the combined impact of wind and surface properties which control the underlying mechanisms of the gas transfer across the interface. Currently, global estimates of air-sea fluxes rely on wind speeds obtained from space-borne radar or theoretical models. These estimates use the empirical Liss-Merlivat relation to infer gas exchange rates from the wind speed. A more direct parameterization, based on remote sensing of wave number specific sea surface roughness would be possible through the use of a relation derived from in situ measurements of short wave spectra and CFT gas transfer rates. A preliminary result of such a parameterization, derived from a data set of the 1997 field experiment is shown in Fig. 2. The extrapolation to a flat surface (zero mean square slope) is consistent with diffusion-limited gas exchange rates.

The spatial structure of the micro-turbulence at the water surface can also be extracted from infrared images of the sea surface temperature. A systematic analysis of the spatial scale and shape of the heat patterns at the water surface shows a clear transition from large-scale (cloudy) structures at low wind speeds to small-scale elongated structures at high wind speeds (Fig. 3). These temperature structures allow a direct insight into the transport processes at the interface and reveal the influence of surfactants on the transport. A quantitative analysis of these structures requires further systematic in-situ measurements.



3. Scale analysis of the sea surface temperature microstructure. *The plot shows the contribution of different spatial scales to the total temperature variance. Larger structures dominate the patterns at low wind speeds, but at higher wind speeds smaller structures can be observed more frequently.*

IMPACT/APPLICATION

The methods developed in this research project are only the beginning of a new interdisciplinary research area that merges chemistry, applied optics, fluid mechanics, and image processing techniques. The interaction between the different fields will provide an unprecedented insight into the mechanisms of small-scale air sea interaction processes (Jähne, 1995; Jähne and Haussecker, 1998).

RELATED PROJECTS

The activities in this project are closely related to the NSF CoOP project "Air-Sea Gas Exchange in Coastal Waters." Both projects focus on the air-sea gas exchange at the interface and thus support each other. In cooperation with the image processing group of the PI at the Interdisciplinary Center for Scientific Computing (University of Heidelberg, Germany), new algorithms are being developed for the local analysis of the surface flow image sequences from the IR image sequences. This research is unit funded by the German Science Foundation (DFG) (Jähne, 1997a and b; Jähne et al, 1998; Haussecker and Jähne, 1998, Haussecker et al, 1999).

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AWARDS

German Association for Pattern Recognition (DAGM '99) conference award for the two contributions:

“A total least squares framework for low-level analysis of dynamic scenes and processes”, authored by H. Haussecker, C. Garbe, H. Spies, and B. Jähne, and

“Differential range flow estimation”, authored by H. Spies, H. Haussecker, B. Jähne, and J. L. Barron.